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The T0 Vector Microprocessor

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Talk Outline

Why Vector Microprocessors?

Torrent Instruction Set Architecture (ISA)

T0 (Torrent-0) Microarchitecture

T0 Implementation and Packaging

Status

Summary

Goal:

High-Performance, Programmable, Scalable DSP Architecture.

Many new applications require high performance DSP, for example, multimedia and human-machine interface.

Algorithms are constantly changing, and not all applications warrant custom hardware development, so need programmable DSP engine.

Software development is a major expense. Desire object code compatibility while scaling parallelism up for performance, or scaling parallelism down for cost.

Solution: *Vector Instruction Set Architecture*

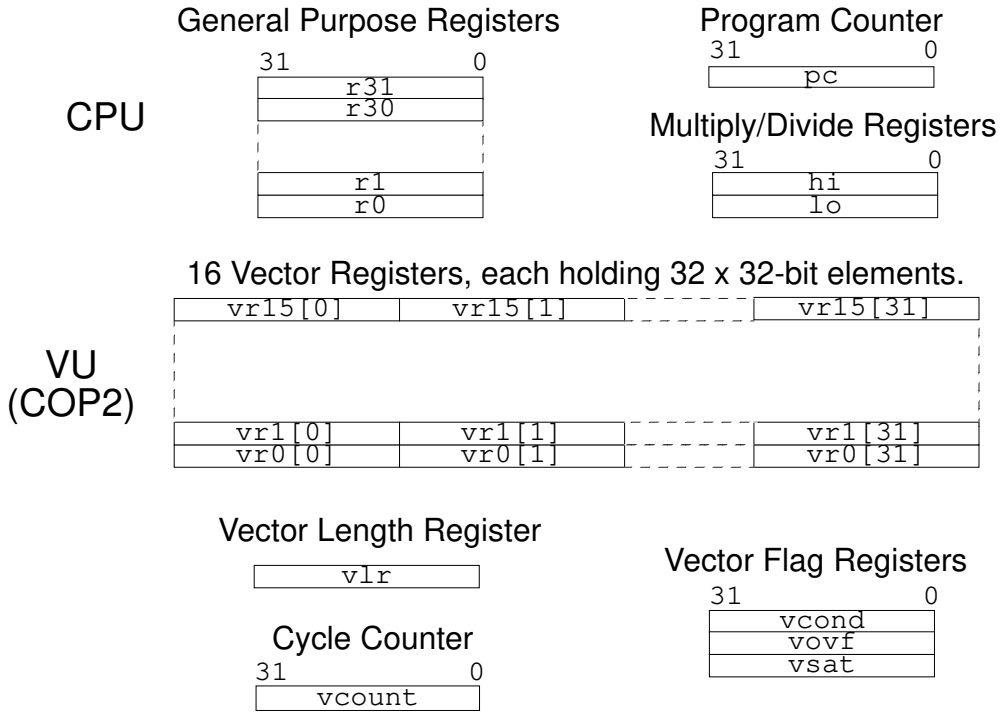
Many compute-intensive DSP operations are vectorizable and vector architectures are the most efficient way to run vector code:

- ❏ Low control complexity.
- ❏ High throughput with multiple parallel and pipelined functional units.
- ❏ Sustain high off-chip memory bandwidth with vector memory operations.

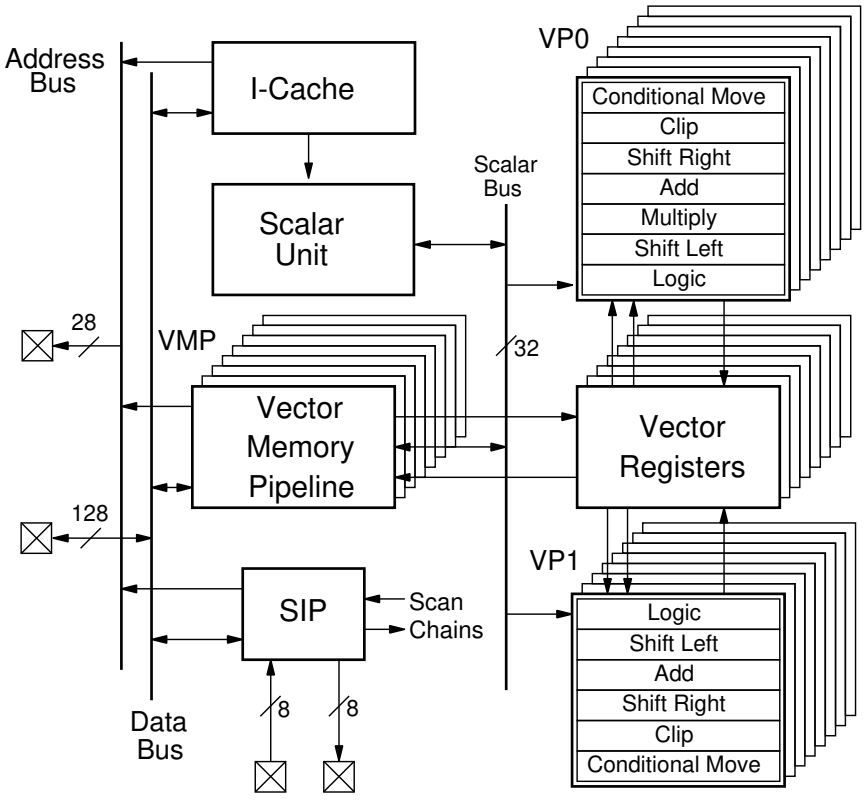
Add to conventional scalar instruction set to preserve software investment.

Scale implementations between low cost and high performance, with same object code.

Torrent User Programming Model



T0 Block Diagram



T0 I-Cache and Scalar Unit

Instruction Cache
1 KB, direct-mapped, 16 byte lines.
Cache line prefetch if memory otherwise idle:
2 cycle miss penalty with prefetch,
3 cycle miss penalty without prefetch.
Service misses in parallel with interlocks.

System Coprocessor 0
Exception handling registers.
Host communication registers.
32-bit counter/timer.

MIPS-II 32-bit Integer RISC CPU
One instruction/cycle in 6 stage pipeline.
Single architected branch delay slot.
Annulling branch likelies.
Interlocked load delay slots.
3 cycle load latency (no data cache).
18 cycle 32-bit integer multiply.
33 cycle 32-bit integer divide.

T0 Vector Memory Operations

Unit-stride with address post-increment

```
lbai.v vv1, t0, t1  # t1 holds post-increment.
```

Eight 8-bit elements per cycle.
Eight 16-bit elements per cycle.
Four 32-bit elements per cycle.
+1 cycle if first element not aligned to 16 byte boundary.

Strided operations

```
lwst.v vv3, t0, t1  # t1 holds byte stride.
```

One 8-bit, 16-bit, or 32-bit element per cycle.

Indexed operations (scatter/gather)

```
shx.v vv1, t0, vv3  # vv3 holds byte offsets.
```

One 8-bit, 16-bit, or 32-bit element per cycle.
+ 3 cycle startup for first index.
Indexed stores need 1 extra cycle every 8 elements.

T0 Vector Arithmetic Pipelines

Full set of 32-bit integer vector instructions: add, shift, logical.

Vector fixed-point instructions perform a complete scaled, rounded, and clipped fixed-point arithmetic operation in one pass through pipeline.

Multiplier in VP0 provides 16-bit x 16-bit -> 32-bit pipelined multiplies.
Scale results by any shift amount.
Provides 4 rounding modes including round-to-nearest-even.
Clip results to 8-bit, 16-bit, or 32-bit range.

VP0 and VP1 each produce up to 8 results per cycle.

Vector arithmetic operations have 3 cycle latency.

T0 Vector Conditional Operations

Vectorize loops containing conditional statements.

Executed in either arithmetic pipeline.

Vector compare:

```
# vv2[i] = (vv5[i] < vv6[i])
slt.vv vv2, vv5, vv6
```

Vector conditional move:

```
# if (vv2[i] > 0) then vv1[i] = vv3[i]
cmvgtz.vv vv1, vv2, vv3
```

Vector condition flag register:

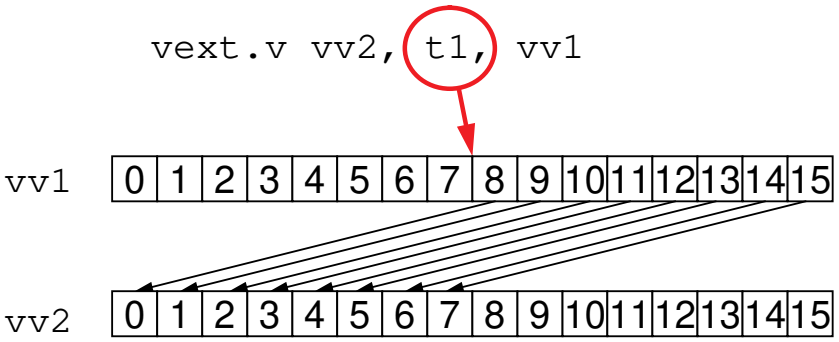
```
# vcond[i] = (vv1[i] < vv2[i])
flt.vv vv1, vv2    # Set flag bits.
cfc2 r1, vcond     # Read into scalar reg.
```

T0 Vector Editing Instructions

Executed in vector memory unit.

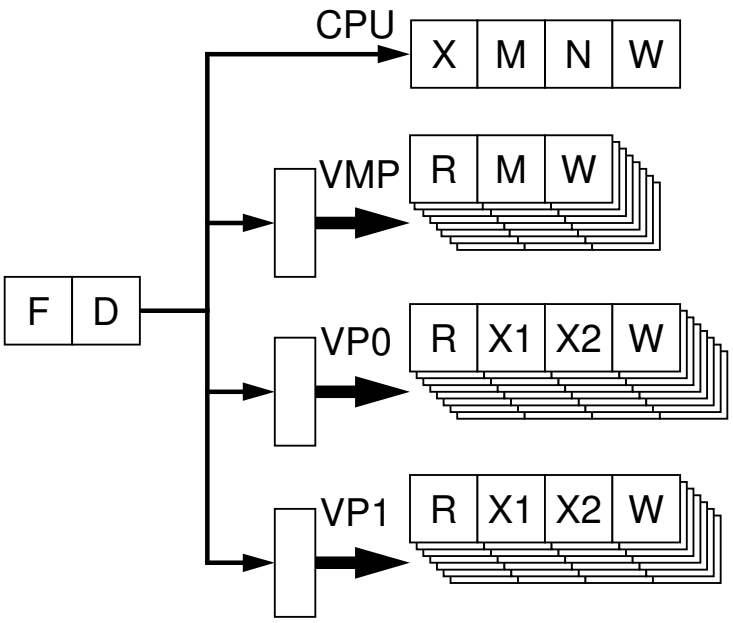
Scalar insert/extract to/from vector register element.

Vector extract supports reduction operations:



Avoids multiple memory accesses.
Separates data movement from arithmetic operations.
Software can schedule component instructions within reduction.

T0 Pipeline Structure

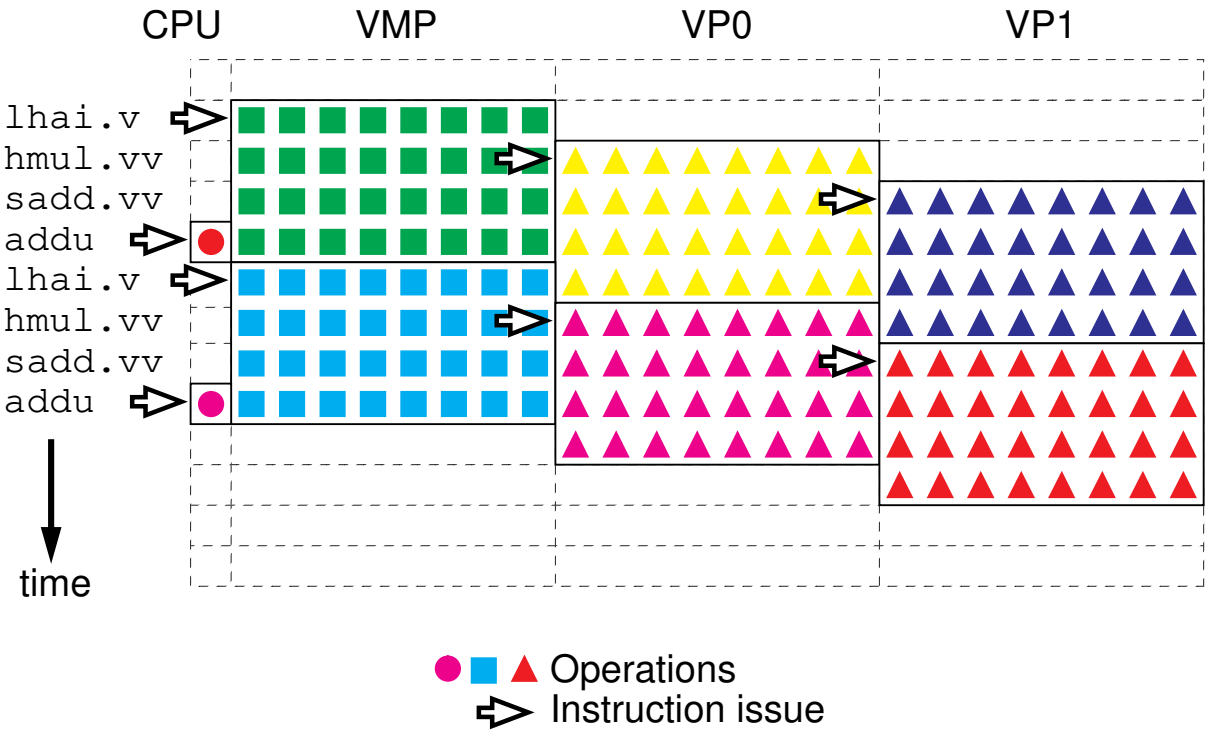


Code Example

```
lhai.v vv1, t0, t1      # Vector load.
hmul.vv vv4, vv2, vv3   # Vector mul.
sadd.vv vv7, vv5, vv7   # Vector add.
addu t2, -1             # Scalar add.
lhai.v vv2, t0, t1      # Vector load.
hmul.vv vv5, vv1, vv3   # Vector mul.
sadd.vv vv8, vv4, vv8   # Vector add.
addu t7, t4             # Scalar add.
```

(taken from matrix-vector multiply routine)

Execution of Code Example



T0 Vector Unit Hazards

All vector unit hazards fully interlocked in hardware.

Vector instruction startup fully pipelined to eliminate strip-mining overhead.

Each functional unit has independent ports into vector register file so no chain slot time and no vector register access conflicts.

All RAW, WAR, and WAW hazards on vector registers fully chained to reduce latency and decrease vector register pressure.

Philosophy: Trade small amount of extra control logic for increased utilization of multiple, expensive datapaths.

T0 External Interfaces

External Memory Interface

- Supports up to 4 GB of SRAM with 720 MB/s bandwidth.
- SRAM access wave-pipelined over 1.5 cycles.
- Industry standard 17ns asynchronous SRAM for 45 MHz.

Serial Interface Port

- Based on JTAG, but with 8 bit datapaths.
- Provides chip testing and processor single-step.
- Supports 36 MB/s host-T0 I/O bandwidth.

Hardware Performance Monitoring

- Eight pins give cycle by cycle CPU and VU status.

Fast External Interrupts

- Two prioritized fast interrupt pins with dedicated interrupt vectors.

T0 Die Statistics

Technology:
1.0 μm MOSIS scalable CMOS rules, 2 metal, 1 poly.
Contacted M1 pitch 3.25 μm
Contacted M2 pitch 3.75 μm
Fabbed in HP's CMOS 26G process.

Die Size: 16.75 mm x 16.75 mm

Transistor Count: 730,701

Clock Frequency: 45 MHz

Power Supply: 5 V

Power Dissipation: <10 W

T0 Status

- ❑ First silicon received 3 April 1995.
- ❑ No bugs.
- ❑ SPERT-II systems running applications.
- ❑ Measured performance on neural net training:

  20x tuned code on Sun Sparcstation-20/61,
  5x tuned code on IBM RS/6000-590.

Summary

With a fully programmable, scalable, vector-register instruction set architecture, T0 sustains up to 720 million arithmetic ops/s while accessing up to 360 million operands/s from main memory, and with up to 36 MB/s of concurrent I/O,

...with roughly 3/4 million transistors (1 Gλ^2),

...at 45 MHz in a 1 μm 2-Al CMOS process,

...in less than 10 person years from no ISA to running applications.